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Fatigue properties of crumb rubber asphalt mixtures used in railways

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HIGHLIGHTS

- Monotonic and cyclic fatigue tests were made on railway asphalt mixtures.
- Crumb rubber modification of railway mixtures considerably increases fatigue life.
- Air void have more influences on railway mixtures compared to highway ones.
- Crumb rubber modification improves railway asphalt mixes more than highway mixtures.
- Findings obtained improve current understanding of low-vibration-railways behavior.

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ABSTRACT

The use of asphalt mixtures in railway tracks provides a positive contribution to the bearing capacity, stability, durability and more importantly damping properties of the railway structure particularly for the new generation of low-vibration-railway track systems. However, one of the main concerns in the use of asphalt mixtures in railways is their fatigue cracking caused by the repeated traffic loading. The present study focused on the fatigue damage behavior of asphalt mixtures in the railways through using the viscoelastic continuum damage theory. Three experiments of creep compliance, constant crosshead rate and cyclic fatigue tests were carried out on some asphalt mixtures with different air void contents and aging conditions. Based on the results obtained, the crumb rubber modification of railways asphalt mixtures at low stress levels increases the fatigue life of asphalt up to 7.2 times while this increase is at the most 3.6 for the highway asphalt mixture. Furthermore, reducing the air void content from 4% to 2% for the crumb rubber modified asphalt mixture increases the fatigue life by 9.4 times at high stress levels and 18.2 times at low stress levels, which is a great improvement. It was shown that the lowest fatigue life is obtained in the aged crumb rubber modified mixture (i.e., 20 percent of unmodified asphalt mixture).

1. Introduction

Railway transportation system is usually preferred over other modes of transportations because of its higher speed, better safety, and less environmental negative impacts. In recent years, with the development of high-speed tracks, this transport system has been given more attention. High-speed tracks require a safer and more reliable railway structure with lower maintenance operations [1,2]. Furthermore, transmission of vibrations to surrounding structures in the urban railways is a serious concern. A very effective solution that improves both the stability and the durability of the structure, contributes to the reduction of need for maintenance operations, and reduces the induced railway vibrations is the use of asphalt mixture in the railway construction [2–6]. Moreover, the use of asphalt mixture makes the possibility of reducing the railway height, and in turn provides great advantages in the construction of tunnels with smaller diameter or lighter bridges. Asphalt mixtures can be used as the ballast layer (Fig. 1a) or the sub-ballast layer (Fig. 1b) in the railway system. According to the literature, the behavior of the overall structure can be improved by using the asphalt mixture as a sub-ballast layer in the track-bed [3]. Also replacing the ballast layer by an asphalt layer can cause more elasticity of the track support system as well as easier construction and maintenance (i.e., easier geometry deviations corrections) [3]. Asphalt underlayment design and construction standards for railways typically follow the recommendations set forth by the Asphalt Institute [7].

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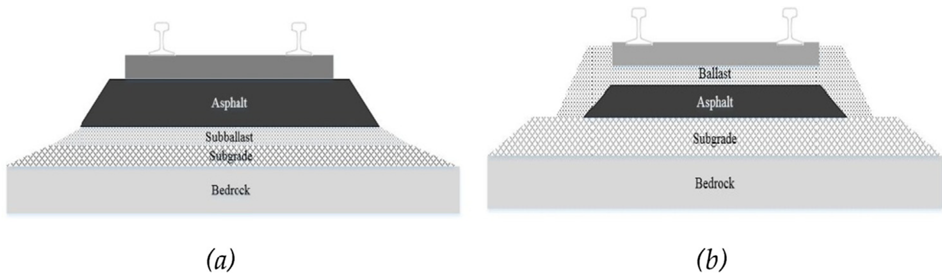

Fig. 1. Schematic views of track-bed using asphalt mixture as (a) ballast layer; (b) sub-ballast layer.

It is generally agreed that fatigue cracking, rutting, and low-temperature cracking are the three principal types of distress considered in the flexible pavement design [8]. However, rutting of the asphalt mixture is not a serious concern in the track-bed, since the pressures are applied through the ballast over a wide area [9] and also the temperatures are not sufficiently high to promote rutting [7]. Bleeding is also of little concern since there is not a direct contact between the wheels and the asphalt layer [9]. However, cracking caused by the fatigue due to repetitive nature of train loads is important in asphalt pavements of railways [10]. This is noteworthy mentioning that the vertical stress levels on the top of the hot mix asphalt (HMA) layer in the railway track-bed are much less than (about one-third of) the one in the highway asphalt layer even with the heavy tonnage of railroad loadings [3,11]. This is due to the wider load distribution of the sleepers on the underneath layer [3]. In 2007, the Design Standard for Railway Structures used by Japanese railway organizations was revised in order to consider the fatigue life of the railway track pavement as it is greatly influenced by the number of passing trains [3,9,12]. The track-bed HMA is specifically designed to have a railway support system with medium modulus, high flexibility, low voids, and fatigue resistance with the ability of bearing high tensile strains without cracking [13]. Recent studies have also indicated that coarse aggregate has an important effect on the fatigue cracking of asphalt mixtures [14]. The typical asphalt mixture used in railway applications is a dense-graded highway base mixture with a maximum aggregate size of 25–37.5 mm [3,15]. In addition, in order to have a low to medium modulus mixture in railway structure, it is usually tried to increase the asphalt binder content by 0.5% over the considered optimum for highway applications. This usually results in an asphalt mixture with a lower air void of 1%–3% [7,15]. This slight modification to the typical highway mixture can impart the ideal properties of the track structure. The positive effect of the air void reduction on the fatigue properties of asphalt mixtures used in highway applications have been evaluated by some researchers. A 1% decrease in air void content was reported to improve the fatigue properties of asphalt mixtures between 8.2 and 43.8% and the rutting resistance by 7.3–66.3% [16]. Harvey et al. showed that a 1% increase in air void content of an asphalt mixture with 5% asphalt content and 5% air voids, causes a 30-percent reduction in the fatigue life [17]. Tao el al. also showed that increasing the air voids from 4% to 6%, 8%, 10% and 12% reduces the fatigue life by 5%, 25%, 30% and 50%, respectively [18]. A review of the available literature indicates that the fatigue properties of asphalt mixtures of railway applications at very low air void contents have not been sufficiently investigated and need further investigations.

The use of special additives or polymer-modified binders can also offer the possibility of complying with specific requirements (heavy duty, lower temperatures, and noise/vibration reduction) for the mixture or the construction [3,15]. In the past few years, various additives, including hydrated lime, cement, amines and polymers were used to improve the physical properties of asphalt mixtures used in the highways. In addition, with the environmental problems of waste tires and the low costs of crumb rubber production in one hand, and the necessity of using vibrations-damping-materials as a base (ballast) in the railway, on the other hand, an investigation of using this material (as an additive) to improve the properties of railway asphalt binder (and mixture) has become an important need in the railway field. Although various studies have been made on the performance characteristics and modeling the behavior of crumb rubber modified asphalt mixtures, crumb rubber mixtures designed and used in the railway track-bed layers have not been sufficiently investigated.

In recent years, many researchers have focused on mathematical and experimental modeling of asphalt fatigue properties. One of these models was based on the fundamental theory of viscoelastic continuum damage, which was first used in 1990 by Kim and Little [19]. They applied the Schapery's nonlinear viscoelastic constitutive theory for the materials with distributed damage in order to describe the sand asphalt mixture behavior under controlled strain cyclic loading [19]. Later on (in 1998), it was shown that the theory of VECD can properly describe the behavior of asphalt concrete under both controlled stress and controlled strain cyclic loadings [20]. In 2001, Daniel showed that the damage characteristics of asphalt materials were independent of the mode of loading and it could be determined using simpler tests [21]. Chehab and Kim (2002) validated the time-temperature superposition principle at high levels of damage [22]. These two findings significantly reduced the required testing protocol while simultaneously extending the scope of application of this model. Later on, Underwood (2006) used polymer modified asphalt and demonstrated that the time-temperature superposition principle was also acceptable for modified bitumen [23]. On the same line, Kutay and Gibson (2008) used a push-pull (tension-compression) test to develop a simplified model for computation of damage in cyclic tests [24]. Haddadi and Ameri (2015) validated the simplified viscoelastic continuum damage model for flexural mode of loading [25]. More recently, Wei and Kim (2016) illustrated the viscoelastic-viscoplastic coupling phenomenon in asphalt concrete using results obtained from experiments [26].

2. Research objective and methodology

As indicated above, despite various studies made on the performance characteristics and modeling of asphalt mixtures, the asphalt mixture (in particular the crumb rubber modified mixture) used in the railway track-bed layers has not been sufficiently investigated. Due to the widespread application of viscoelastic continuum damage (VECD) theory in modeling the fatigue properties of asphalt mixtures in one hand, and the necessity of using fatigue life and fatigue damage models in the design of asphalt mixtures used in the track-bed on the other hand, the VECD model was used